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HUNTSVILLE, ALABAMA

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DEMONSTRATION OF THE USE OF COMPOSITE PLASTISOL NITROCELLULOSE PROPELLANT IN A SHORT-BURNING ROCKET (U)

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Report No. S-55

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ABSTRACT

The Tube-launched, Optically-tracked, Wire-guided anti-tank weapons system required a short-burning, high-thrust booster to provide the necessary launch acceleration. Typically, motors made using cartridge-loaded charges of tubular M-7 stick propellant have filled this type of requirement. This Division was asked to determine the feasibility of using a cast propellant charge in this unit.

The functioning of case-bonded, thin-web wagonwheel grains of composite plastisol nitrocellulose propellant was studied experimentally in a 2-inch inside diameter rocket motor. Nominal conditions were 4000 psia chamber pressure, 7000 lbf thrust, and 0.04 seconds burning time. Constant cross-section grains functioned poorly at temperatures above +20°F. Doubling the propellant tensile strength by composition adjustment did not improve performance. Interrupted-burning studies elucidated the grain failure mechanism and indicated solutions to the problem. A tapered modification of the basic grain functioned well at temperatures up to +120°F. Ignition rise times under three milliseconds were obtained using either aft- or head-end-mounted systems. Provision for axial direction of the igniter products was necessary to prevent damage to the grain. Operation at higher pressures would have eliminated many of the mechanical problems, but a change of propellant burning rate exponent to $\geqq 1.0$ occurred at pressures only slightly above design. Substituting a different oxidizer increased the exponent break pressure but also increased the smoke produced during burning.

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DEMONSTRATION OF THE USE OF A COMPOSITE PLASTISOL NITROCELLULOSE PROPELLANT IN A SHORT-BURNING ROCKET

The Tube-launched, Optically-tracked, Wire-guided (T.O.W.) anti-tank weapon system requires a high-thrust, short-burning rocket motor to accelerate the missile to a velocity of 150 feet/second before it leaves the 6-foot launcher tube. The tactical specifications include temperature limits of -25°F and +125°F, a maximum action time at -25°F of 50 milliseconds, smokeless operation, and a total impulse of 280 lbf-sec. The flight unit has an outside diameter of 2.1-inches and an overall length of 17-inches. The missile acceleration is about 300 g's.

Typically, extruded double-base propellants such as M-7 have been used in such applications, but in an effort to simplify motor manufacture the feasibility of meeting specifications on the TOW booster with a cast, case-bonded grain of composite plastisol nitrocellulose propellant was investigated by this Division. The objectives of the program were to

(1) design a suitable grain

(2) modify propellant compositions to give maximum performance

(3) static-test motors to determine performance over the required temperature range.

1. Motor Development

1.1 Grain Design

Propellants which could be easily processed, which had well-characterized ballistic properties, and which could withstand long-term storage were required. For these reasons chemical and physical burning rate modifiers were not considered, limiting burning rates to approximately 2 inches/second at 4000 psia. Designing a motor to operate at higher pressures than this was considered to be undesirable because the propellant pressure exponent increases at pressures slightly above

4000 psia. Using RH-P-163 propellant (Table I), the available pressure and burning rate could satisfy the required thrust level and burning time only in a thin-web, high-surface wagonwheel grain having a high initial throat-to-port ratio (J_o). The combination of a relatively fragile grain, high acceleration, and a high J_o was not attractive, but there was no practicable alternative within the state-of-the-art.

Table I

RH-P-163 Composition

Components		Wt. %
Double-base powder		16.7
Triethylene glycol dinitrate (TEGDN)		37.3
Ammonium perchlorate	10-15μ mean diameter	35.2
	140-190μ mean diameter	8.8
Aluminum		1.0
Resorcinol		1.0

The wagonwheel grain design graphs[1] were used to define the general dimensions of the proposed grain, and a computer program was used to calculate the final web and spoke length. The result was a modified wagonwheel grain having round spoke tips (Fig. 1). This grain had a more nearly neutral surface/web history than a conventional sharp-spoke wagonwheel having the same loading fraction.

The initial design was modified by tapering the spokes uniformly from head to tail (Fig. 1). This change brought about an 11% reduction of J_o while maintaining surface area and volumetric loading constant. The characteristics of both straight and tapered grains are tabulated in (Table II).

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[1] "A Practical Mathematical Approach to Grain Design" by M. W. Stone, Jet Propulsion, 28, 4, April 1958.

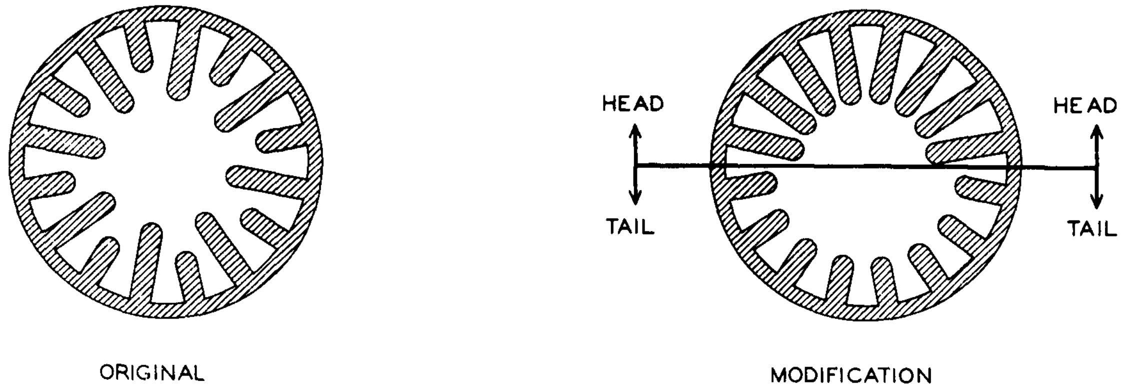


Fig. 1 Original grain design and tapered modification.

Table II

Important Parameters of TOW Grain

	Straight Grain			Tapered Grain		
	Long	Short	Average	Head	Tail	Average
Length, in	15.0			15.0		
Outside diameter, in	2.0			2.0		
Web, in	0.070			0.070		
Surface Area, in^2	290			290		
Sliver fraction, %	4.6			4.6		
Cross-sectional loading, %	50.0			56.3	43.6	50.0
Port area, in^2	1.57			1.37	1.77	1.57
Spoke length, in	0.427	0.247	0.337	0.427	0.247	0.337
Number of spokes	16			16		
Weight of grain, lbm	1.2			1.2		

Simplified calculations indicated that stresses of the order of 50 psi could develop in the spokes as a result of gas drag, pressure drop, and acceleration. However, the duration of the stress was short and it was assumed that the grain could withstand the stresses.

1.2 Experimental Program

1.2.1 Ignition Development

The first motors tested were ignited with a conventional center-mounted RHim[1] bag igniter. Results showed that the RHim bag was too brisant; changing the location from the center of the grain to the aft end, changing from RHim to black powder, and placing the igniter inside a tube to direct the gases axially (Fig. 2) all reduced the ratio of maximum pressure to average pressure (Table III). A bag igniter inside a forward-mounted pyrogen assembly (Fig. 3) produced results roughly equivalent to the aft-mounted tube (Table IV), and these ignition systems were used almost interchangeably.

Table III

Effect of Type, Location, and Material of Igniter on TOW Performance at +77°F

Round	Type	Location	Material	P_{max}, psia	P_{max}/P_b
884	5 gm-bag	Center	RHim	6426	2.92
885	5 gm-bag	Center	RHim	8449	3.52
921	5 gm-bag	Aft	RHim	3738	~2.5
950	5 gm-bag	Aft	Black powder	4849	2.05
951	5 gm-tube	Aft	Black powder	4998	2.05
952	5 gm-tube	Aft	Black powder	6942	2.13

[1]Rohm & Haas Igniter Material; 60% Magnesium, 15% Barium Nitrate, 25% Potassium Perchlorate.

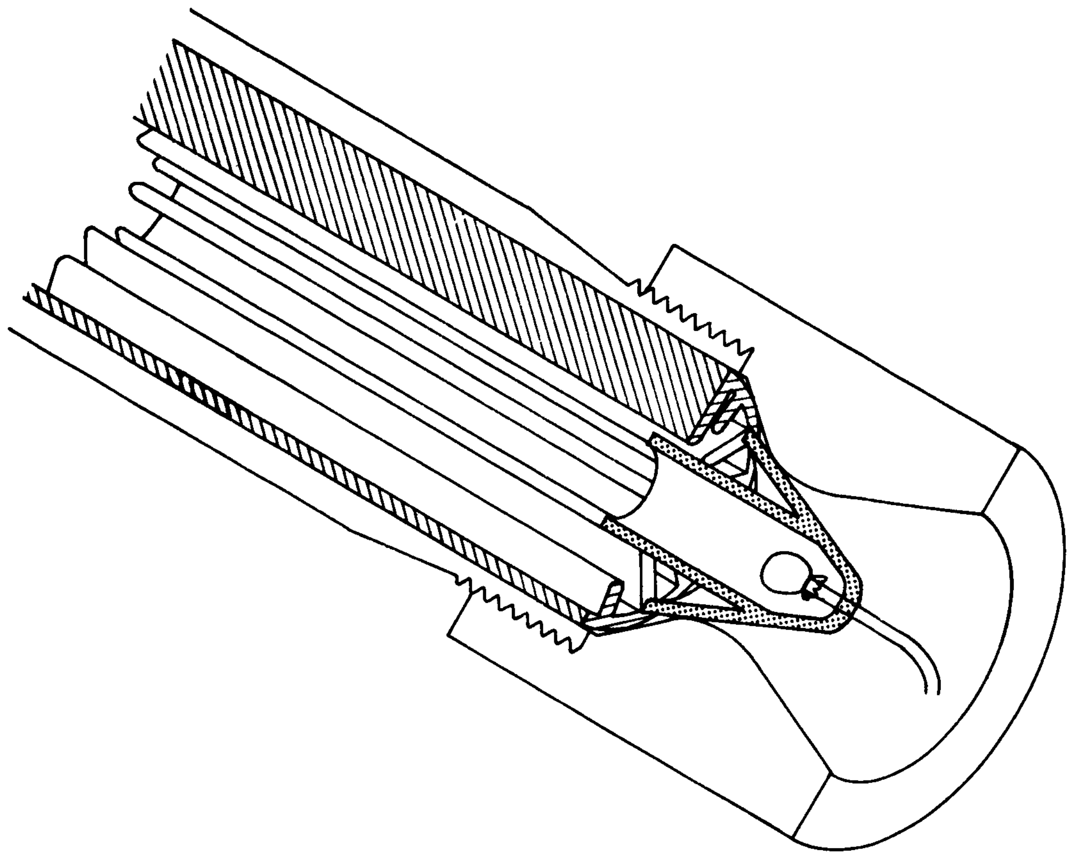


Fig. 2 Nozzle-closure igniter system.

Table IV

Comparison of Aft-Mounted Tube and Forward-Mounted Pyrogen Igniters at +20°F

Round	Type	Location	P_{max}, psia	P_{max}/P_b	$C_{DO} \times 10^3$ lbm/lbf-sec
1191	Tube	Aft	5070	1.31	6.44
1206	Pyrogen	Head	4803	1.35	6.47

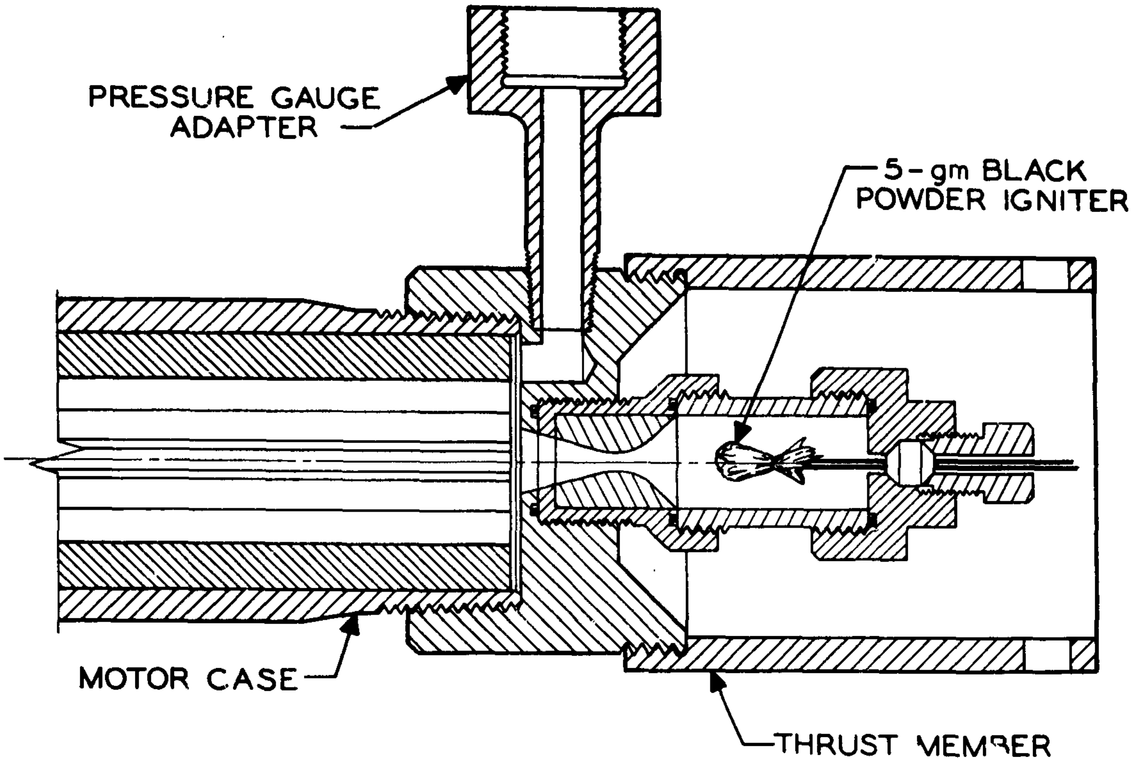


Fig. 3 Bag igniter in a forward-mounted pyrogen assembly.

1.2.2 Effect of Propellant Strength

Firings of the straight grain at +77° F with RH-P-163 propellant gave indications that the grain was breaking up under the severe flow conditions imposed upon it (Table V, Fig. 4). The high discharge coefficients (C_{DO})[1] and pressure spikes are characteristic of this mode of failure. Since the propellant failed even though the stresses were of short duration, an attempt was made to improve propellant mechanical properties without changing ingredients or processing characteristics. Significant strength improvements at +77° were obtained

[1]A more complete definition of this and other ballistic parameters is included on page 22.

when the plasticizer/powder ratio was reduced, but the improvement at +140°F (Table VI, Fig. 5) was much smaller. Even the strongest propellant did not improve the performance of the straight grain at +77°F, although the pressure-time records from firings at +20°F and below were acceptable when the original propellant was used (Fig. 6). The successful low-temperature firings indicated that the minimum strength required at +140°F would be approximately 120 psi; the possibility of developing this tensile strength seemed to be quite small. Efforts were consequently redirected toward the development of a motor having a tapered grain.

Table V

Results of Initial TOW Firings

Round	P_{max}, psia	$P_{max}/\overline{P}_b$	$C_{DO} \times 10^3$ lbm/lbf-sec
884	6426	2.92	7.55
885	8449	3.52	7.46
886	5555	3.35	7.07

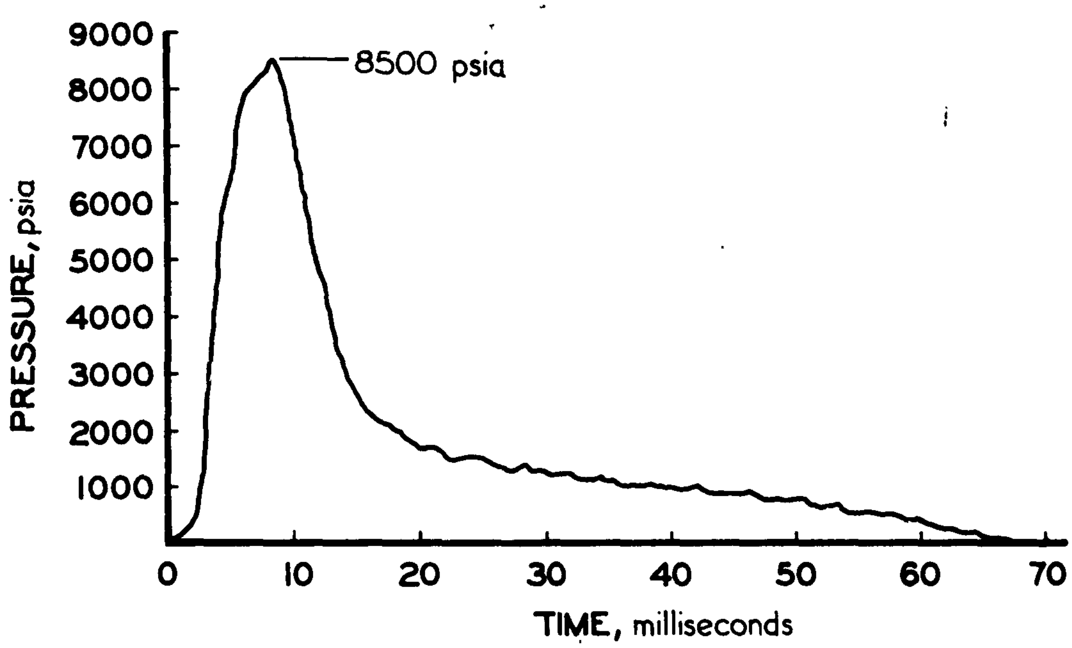


Fig. 4 Typical pressure trace of a straight grain fired at +77°F.

Table VI

Tensile Properties of TOW Candidate Propellants

Propellant	TEGDN/Powder Ratio	Uniaxial Tensile Strength, psi, At Given Temperature 0°F	+77°F	+140°F
RH-P-163	2.0	250	50	40
RH-P-376	1.7	260	80	58
RH-P-382	1.3	425	111	66

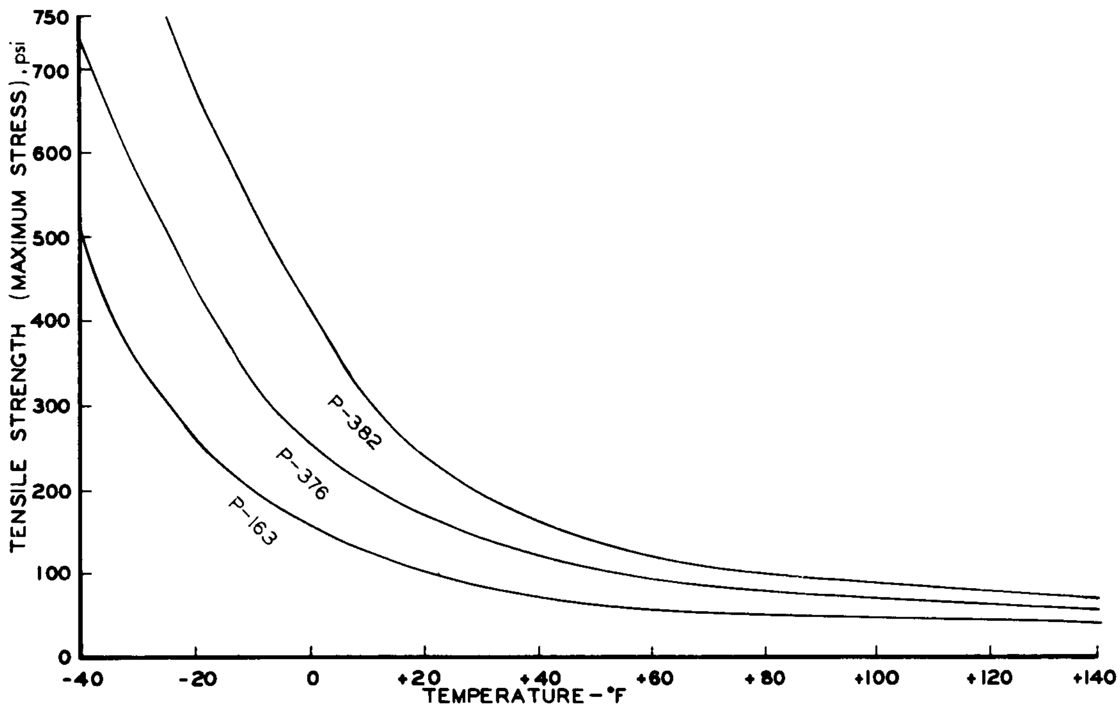
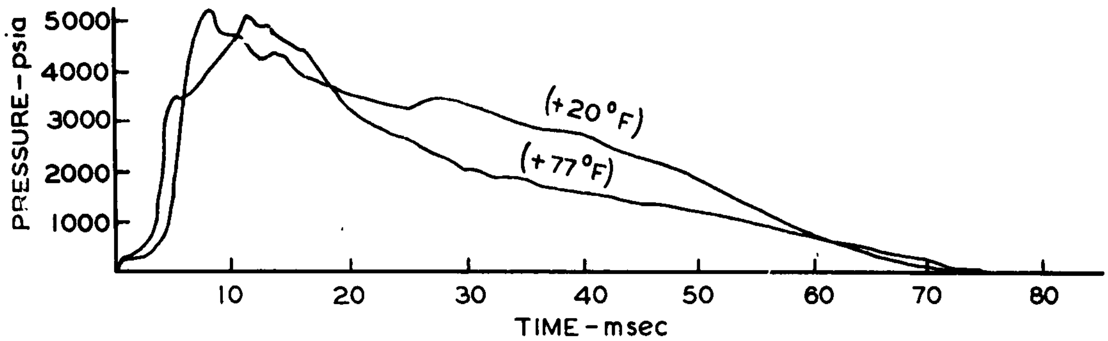


Fig. 5 Tensile strength of several propellant modifications as a function of temperature.



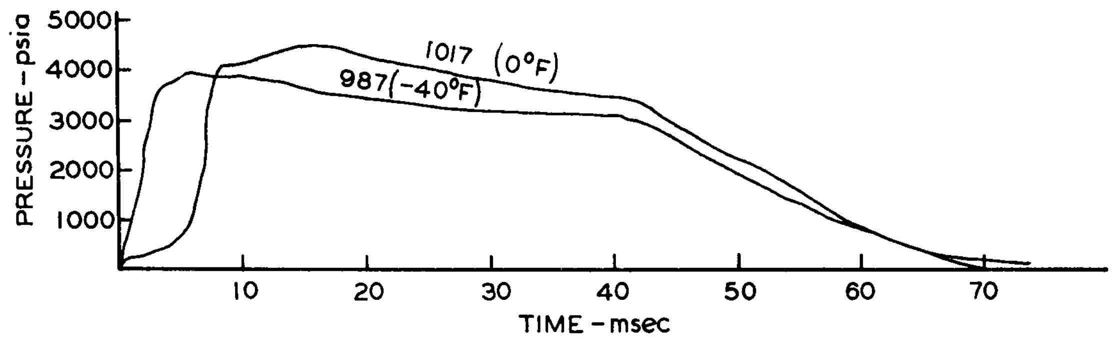


Fig. 6 Effect of firing temperature on the performance of the straight grain motor.

Firings with RH-P-163 in motors having tapered grains were similar to the previous firings of straight-grained motors, except that the amount of ejected propellant was less, and the pressure started to round over at the design level (Table VII, Fig. 7). Using RH-P-382 gave good results at temperatures up to +120°F (Table VIII, Fig. 8), except that the total impulse delivered was lower than desired. At +130°F, there were indications of propellant breakup near web burnout (Fig. 9). The pressure spike at -40°F (Fig. 8) was caused by excessive closure stiffness.

Table VII

Comparison of RH-P-163 Firings in Straight and Tapered Grains

Round	Type	Temp., °F	P_{max}, psia	$\overline{P}_b$, psia	$P_{max}/\overline{P}_b$	$C_{DO} \times 10^3$ lbm/lbf-sec
886	Straight	+77	5555	1635	3.35	7.55
1944	Tapered	+77	off scale	7634	----	6.52
2033	Tapered	+77	9397	(a)	----	6.86
2217	Tapered	-30	6746	3006	2.24	6.13

(a) $\overline{P}_b$ could not be determined.

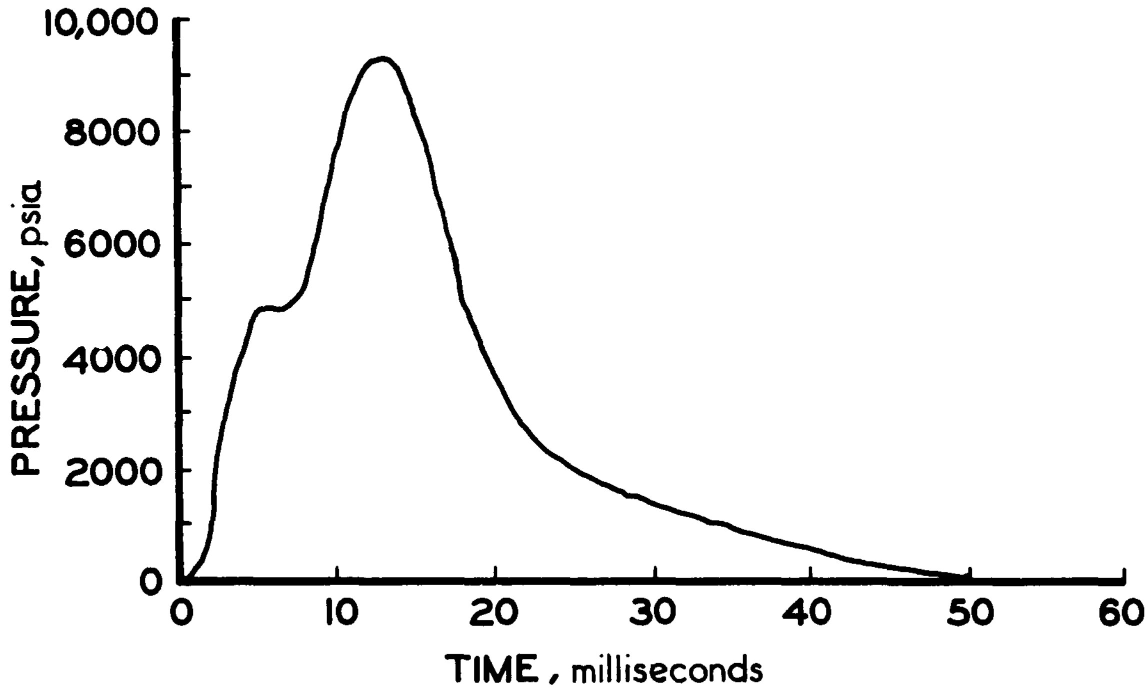


Fig. 7 Initial pressure trace obtained with a tapered grain. Pressure after initial rise remained at the design value for a short time.

Table VIII

Firing Results from Tapered Motors

RH-P-382 Propellant

Round	Temp., °F	t_b, sec	P_{max}, psia	$\overline{P}_b$, psia	$P_{max}/\overline{P}_b$	$C_{DO} \times 10^3$ lbm/lbf-sec	Fdt, lb_f-sec
1894	+77	0.036	4016	3639	1.10	6.23	----
1900	+120	0.024	5233	4516	1.14	6.27	----
1905	+77	0.033	4506	3956	1.14	6.17	231.3
1909	+130	0.023	7938	5189	1.53	6.28	225.8
1917	-40	0.049	6094[a]	2905	2.10	6.37	232.5
1993	+130	0.024	6104	4789	1.27	6.48	226.9

[a]Closure too stiff at -40°F.

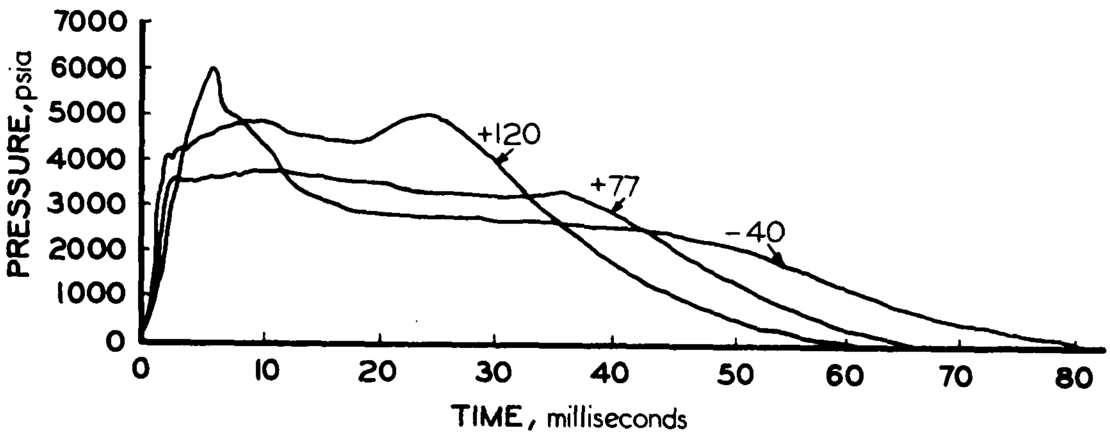


Fig. 8 Typical pressure traces obtained with tapered grains of RH-P-382 propellant.

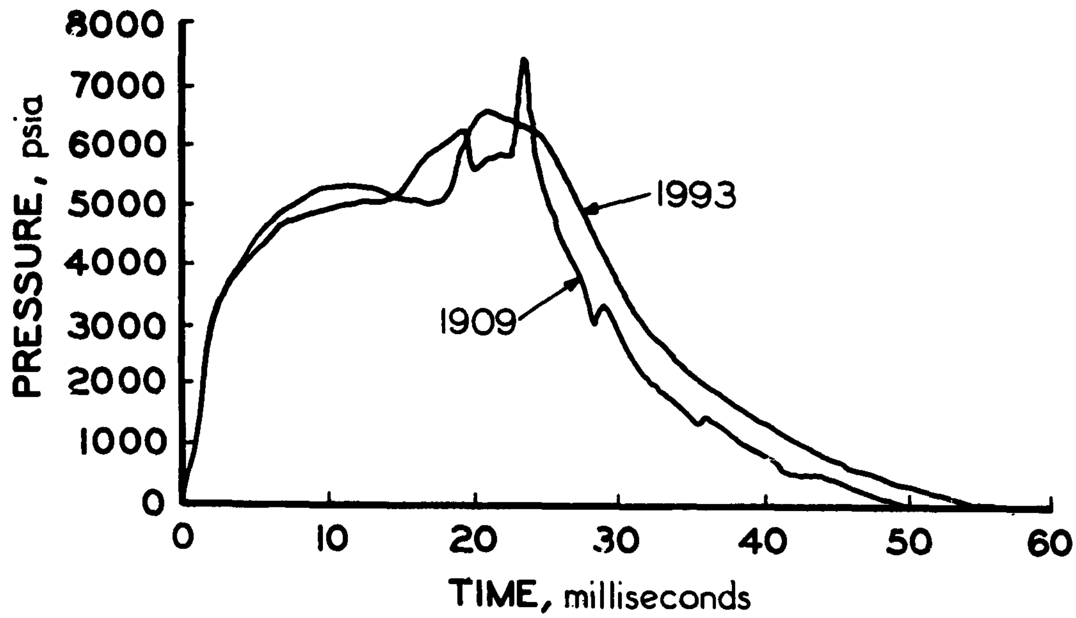


Fig. 9 Two pressure traces obtained with tapered grains of RH-P-382 propellant at 130° F.

These results were promising enough to warrant one further attempt at improving high-temperature strength. Using RH-P-382 as a starting point, the effect of replacing triethylene glycol dinitrate (TEGDN) with metriol trinitrate (TMETN) was investigated. Strength at +77°F was increased significantly but there was little increase in the strength at 120-140°F.(Table IX, Fig. 10). Since there seemed to be no simple way of obtaining more strength in a processable nitrocellulose system, the effort was abandoned.

Table IX

Effect of TMETN on Tensile Properties[a]

Wt. % TMETN/TEGDN	Tensile Strength, psi/Strain at Maximum Stress, in/in, at temperatures indicated. +77°F	+140°F
0/33.4	96/12	59/12
3.33/30.1	100/11	58/14
6.7/26.7	95/11	52/13
10.0/23.4	106/11	55/12
16.7/16.7	114/10	56/12
23.4/10.0	131/11	62/14

[a]Measured Using R & H #2 specimen at 33% relative humidity.

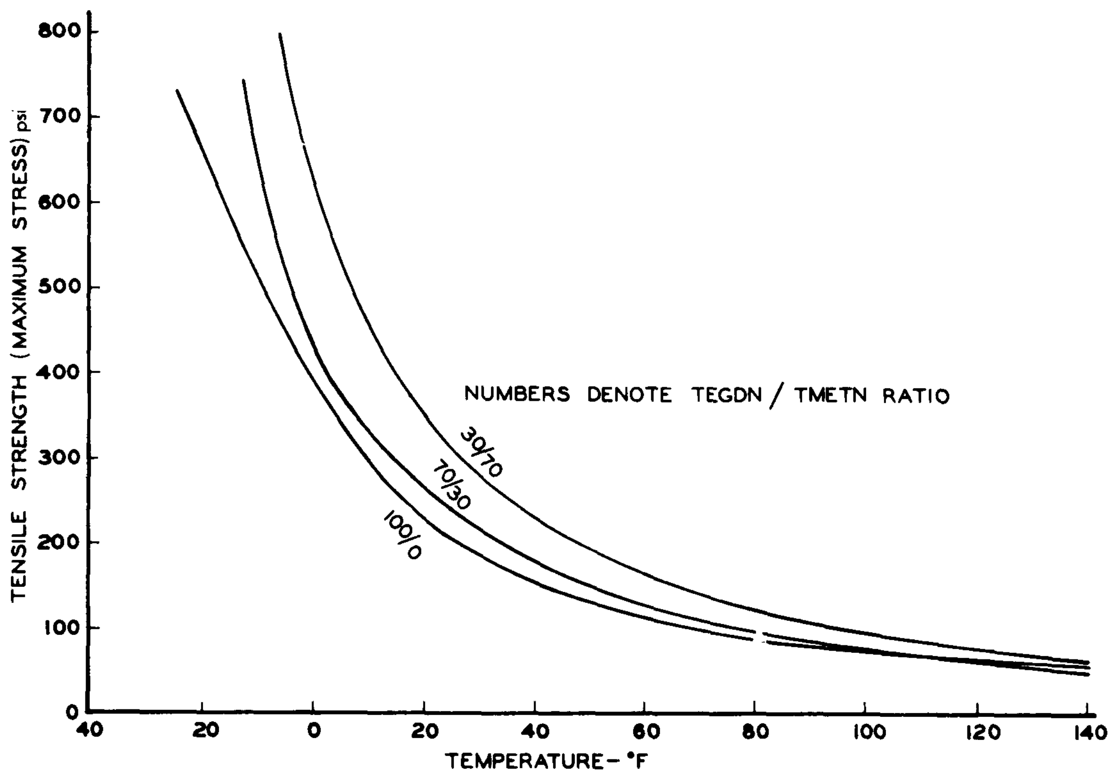


Fig. 10 Tensile strength of several propellant modifications as a function of temperature.

1.2.3 Effect of Initial J

Several motors fired at various values of J_o indicated that there was a significant effect of that variable on grain integrity (Table X). Decreasing J_o tended to decrease C_{DO}, which indicated a reduction in grain breakup. Most significant, however, was the fact that with the straight grain, motor performance at +77°F was poor even at a J_o value of 0.45; this J_o was low enough to reduce axial forces on the grain to less than 15 psi. At the same time, tapered grain tests were successful at J_o = 0.56. This indicated that forces other than those normally considered were responsible for the grain failures; the mechanism was by no means straightforward.

Table X

Effect of J_o on Propellant Breakup

Straight Grains at +77°F

Round	Throat Diameter in	J_o	P_{max}/P_b	$C_{DO} \times 10^3$ lbm/lbf-sec
886	1.318	0.87	3.35	7.43
950	1.220	0.75	2.05	7.86
951	1.200	0.72	2.05	7.62
900	1.129	0.64	2.75	7.07
1326	1.127	0.64	2.85	7.00
924	0.965	0.47	1.74	6.99
922	0.926	0.43	1.42	6.80

Obtaining the required thrust from a motor with a J_o low enough to eliminate breakup with RH-P-382 at +130°F would require a pressure of more than 4000 psi. Propellants which contain potassium perchlorate (KPC) as the oxidizer have no break-point, but these propellants are also too smoky for most applications. An attempt was made to develop a propellant having a higher break-point pressure and an acceptable smoke level using mixtures of APC and KPC (Table XI). As expected, replacing APC with KPC increased both smoke level (Table XII) and break pressures (Fig. 11). RH-P-383 had a break pressure greater than 6000 psia; if the motor were operated at this pressure, J_o could be reduced by 50% with a probable reduction in high-temperature breakup if propellant mechanical properties were similar to RH-P-382. Unfortunately, the tensile strength of the propellant decreased with increasing KPC content, because of larger particle size and lower volume fraction of solids, and the J_o reduction effect could not be evaluated fairly in the time available. A propellant containing only potassium perchlorate as the oxidizer could be used at pressures greater than 10,000 psia and J_o values of less than 0.5.

Table XI

Propellant Compositions Using $KClO_4$ and NH_4ClO_4

Component	RH-P-382	RH-P-383	RH-P-386
Double-base powder	25.6	25.6	25.6
TEGDN	33.4	33.4	33.4
Ammonium perchlorate (APC)	39.0	19.5	----
Potassium perchlorate (KPC)	----	19.5	39.0
Aluminum	1.0	1.0	1.0
Resorcinol	1.0	1.0	1.0

Table XII

Effect of KPC Content on Smoke Production

Composition	% Visual Transmission
RH-P-382	15
RH-P-383	8
RH-P-386	Approx. 0

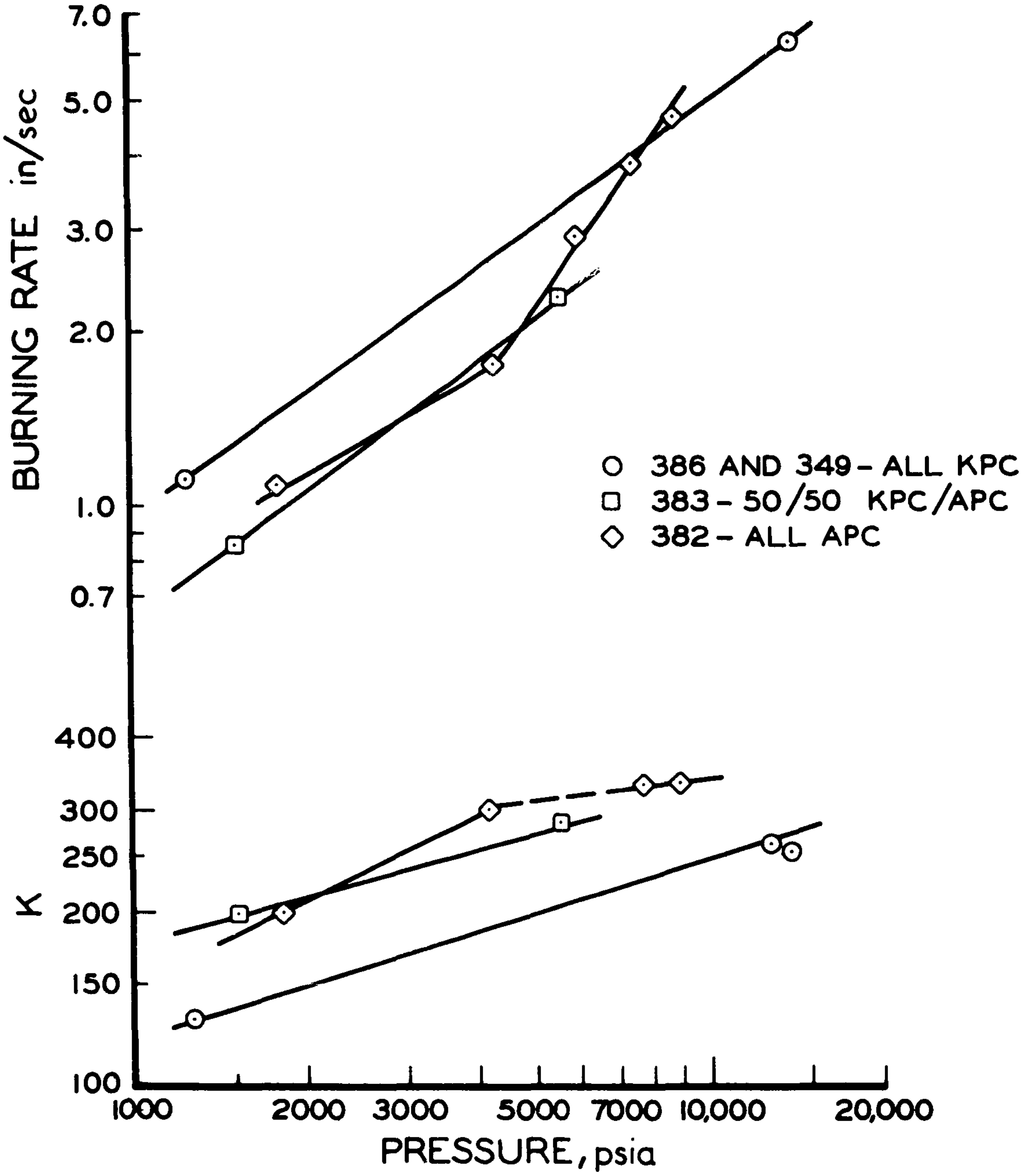


Fig. 11 Burning rates and P-K values for propellants modified with potassium perchlorate.

1.2.4 Study of Failure Mechanism

The grain failure mechanism was not well understood, but several general observations could be made.

(1) All straight grains fired at ambient temperature gave poor traces, regardless of propellant.

(2) Tapered motors were generally successful when RH-P-382 was used.

(3) Firings of straight and tapered grains at reduced temperatures were successful, but the discharge coefficients tended to be high even when trace shapes were acceptable.

(4) High-speed movies (3000-5000 frames/sec) did not show propellant particles in the exhaust plume even though the high discharge coefficients and cardboard witness screens both indicated that unburned propellant was ejected.

(5) The motors having the highest P_{max}/P_b ratios generally had the lowest discharge coefficients.

Interrupting a motor during operation was necessary to give a clear picture of the failure mechanism, and equipment was built for this purpose. A rapid pressure reduction with a blow-out disk extinguished the grain and a water quench prevented reignition. The experimental setup is shown in Fig. 12. Examination of a straight grain extinguished after 15 milliseconds showed that the aft 4-inches of the spokes had been removed, and several of the spokes still attached had burned through at the point of attachment to the cylindrical web (Fig. 13). These pieces probably would have been ejected within a very short time had burning been allowed to continue. A tapered grain, on the other hand, lost much less propellant in the same length of time and did not show the same evidence of accelerated burning at the spoke base.

The apparent accelerated burning could be explained in the following way. The strain capability of these high-strength propellants is not great. If flow disturbances could cause a tendency toward tangential flow, the long spokes of the straight grains would be subjected to large bending forces. These forces would cause large strains at the base of the spokes, causing cracks and/or an increased burning rate in the area of highest strain, and promoting propellant breakup. The loss of any propellant would disturb the flow still more and could lead to a chain reaction effect. The tapered grain, on the other hand, has shorter spokes and a less restricted flow area in the critical aft end of the motor. Both of these conditions would lead to smaller stresses on the spokes; there would be less accelerated burning and less tendency toward breakup.

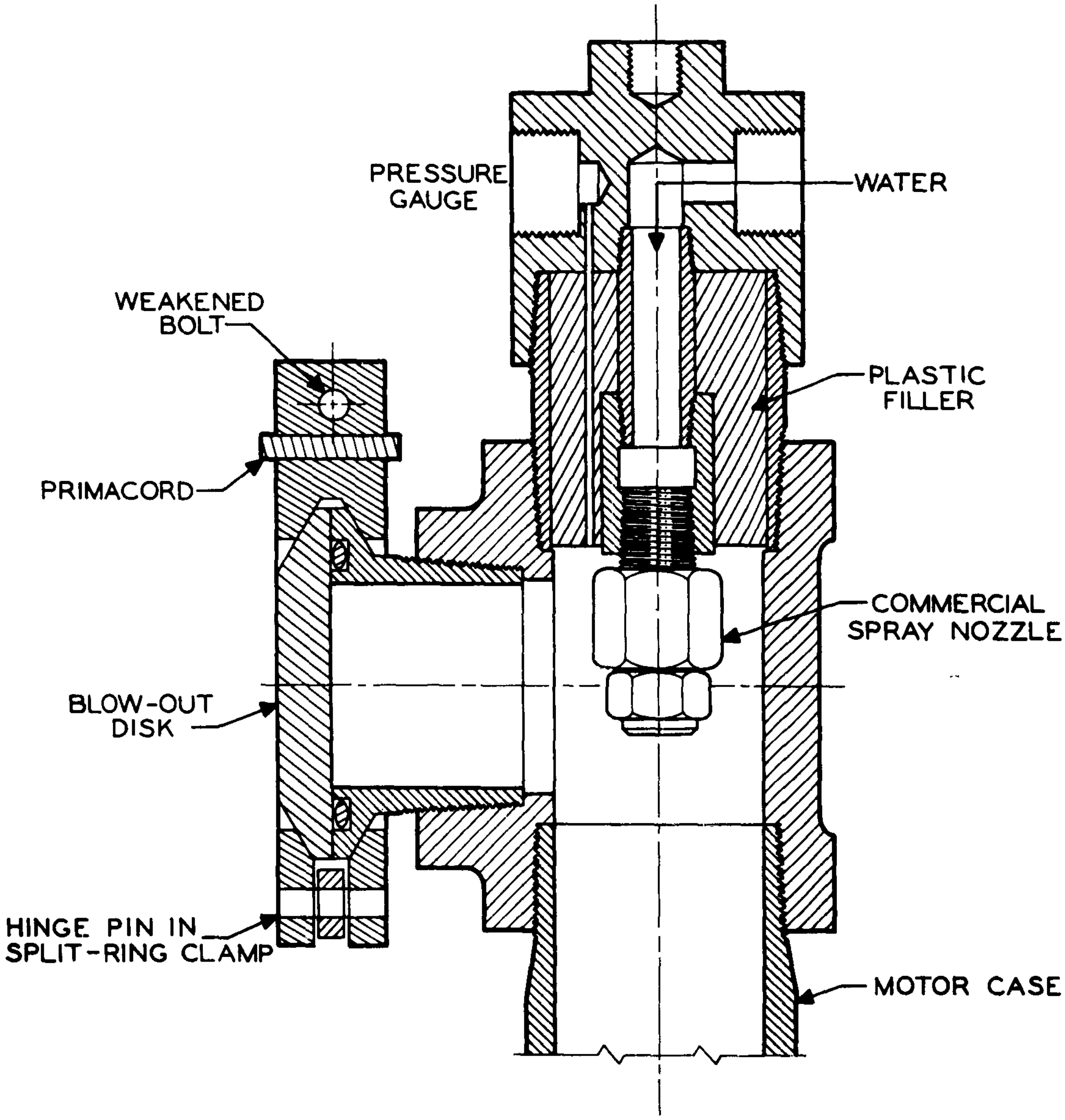


Fig. 12 Experimental set up used to interrupt combustion.

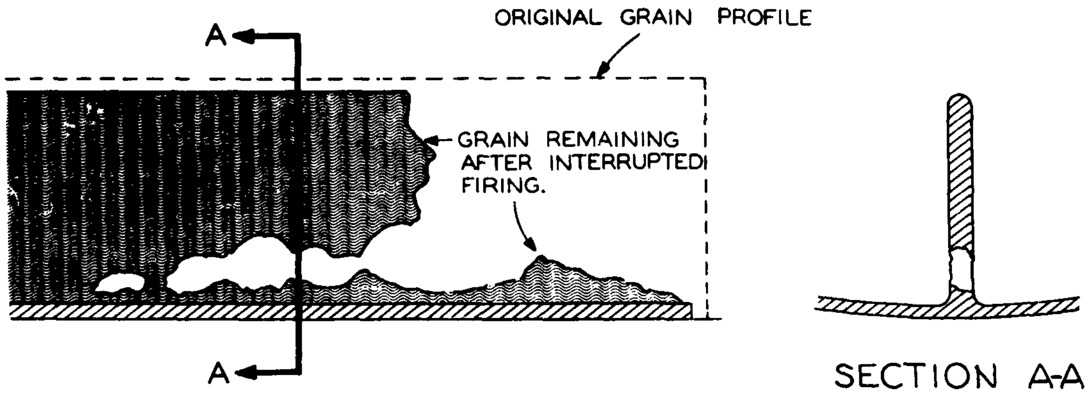


Fig. 13 Sketch showing the appearance of a propellant spoke after interrupted firing.

Successful firings of the straight grain at low temperature indicated that the propellant strength was increased sufficiently by the temperature reduction to prevent massive breakup. Neglecting the other effects of the reduced firing temperature, the straight grain requires a propellant that is at least twice as strong as that necessary for the tapered grain (Fig. 10).

The fact that discharge coefficients were slightly high even when trace shapes were acceptable, supported by the presence of perforations in the witness screens, strongly indicated that some breakup occurred in all motors. Since the motors were operating at a high pressure and the pieces broken off were very thin, much of the debris could burn before leaving the nozzle. Only very small pieces traveling at high speed would leave the motors, and these would be difficult to see in the high-speed movies. Since the rate of consumption of the broken bits of the grain would be a direct function of the maximum pressure, the discharge coefficient would necessarily be an inverse function of the maximum pressur as was observed. At low temperature, only a relatively small amount of grain failure would occur; however, since the pressure would be low, much of this propellant could leave the nozzle unburned. The measured discharge coefficient would then be higher than if the same amount of failure had occurred at a higher temperature.

2. Conclusions and Recommendations

The problems associated with the case-bonded TOW launch motor grain were almost entirely a result of insufficient support for the thin spokes. Reducing the ratio of supported grain area to supporting area or supporting strength would solve much of the difficulty. The tapered grain using RH-P-382 very nearly met the specifications; however, an increase in propellant mass and a decrease in burning time were necessary. Rather minor modifications to the motor would result in a useful tactical unit. However, rocket motors using ammonium perchlorate can never be considered to be smokeless, especially at high humidity.

There are several modifications to the grain and/or propellant that could improve the utility of a unit such as this.

(1) Use of potassium perchlorate as the only oxidizer. This unit would be smoky but would present no serious flow or structural integrity problems.

(2) Use of a propellant similar to M-7 which would be castable and case-bondable. The burning rates available would probably be low, but operating pressure would be no limitation and smoke would be absent.

(3) Use of one of the high-energy, smokeless propellants based on nitrocellulose, TEGDN or TMETN, and RDX. There are propellants in this family which have acceptable temperature coefficients, are smokeless, but have low burning rates. There should be no pressure limitation on these propellants.

(4) Improve the tapered grain for use with a faster-burning modification of RH-P-382. The web should be increased by about 0.005-inches. This motor would be feasible at 4000 psia (+77 °F) and could probably

perform successfully over the required temperature range. The support for the spokes could possibly be increased by increasing the radius at the base of the spokes and/or tapering the spoke slightly from base to tip.

Definitions of Ballistic Parameters

C_{DO} Discharge Coefficient (C_D) corrected for pressure drop along the grain length, lbm/lbf-sec.

$$C_{DO} = C_D \times \frac{\text{Head-end pressure}}{\text{Aft-end pressure}}$$

J_o Ratio of nozzle throat area to initial grain port area at aft end.

P_{max} Maximum head-end pressure, psia.

$\overline{P}_b$ Head-end pressure averaged over the burning time, psia.

$\int Fdt$ Total impulse, lbf-sec.

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